Session 404: Intro to Marine Composites Design- The Basics

Dr. Paul H. Miller, PE
U. S. Naval Academy

Intro to the Intro!

- Goals:
  - "Traditional" methods for marine composites design
  - A good starting point with some directions
  - Some "lessons learned the hard way" (also called "case studies")
  - Some entertainment value!

The big "however"!

My assumptions!

- You have had enough coffee to stay awake!
- You have some background in composites fabrication
  - You know what the common fibers and resins are (E-glass, epoxy, etc.)
  - You know the basic English units of length, force, area, time
  - You are not an engineer!

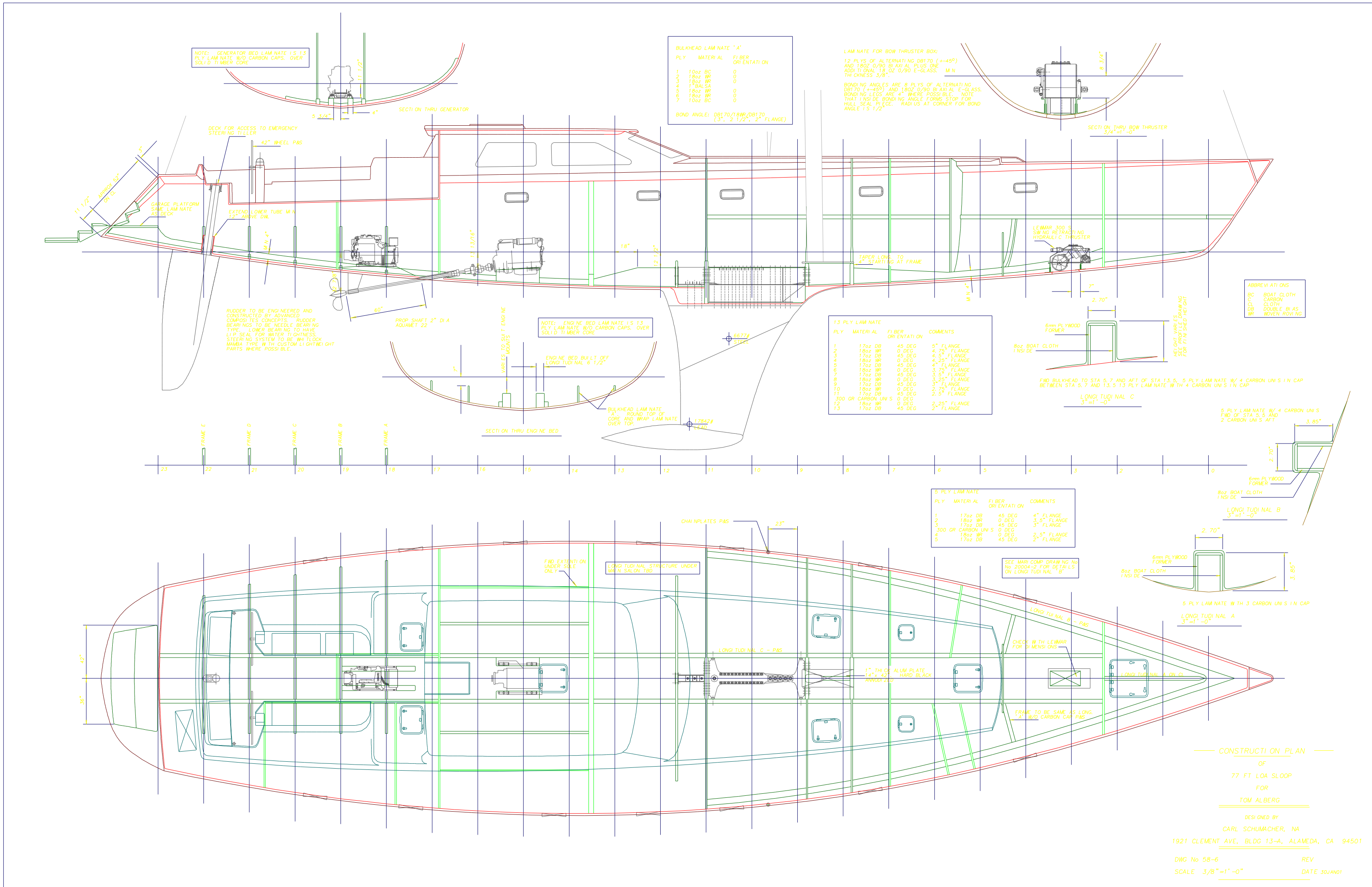
What is “design”?
(from the dictionary)

- The purposeful arrangement of parts
- To create in a highly skilled manner
- A drawing or sketch

What is “Marine Composites Design”?

- Intelligent selection and combination of materials (resins, fibers, cores) to create a structure that fulfills a customer’s requirements
- Communicating that information!

Drawing



CONSTRUCTION PLAN
OF
77 FT LOA SLOOP
FOR
TOM ALBERG
DESIGNED BY
CARL SCHUMACHER, NA
1921 CLEMENT AVE, BLDG 13-A, ALAMEDA, CA 94501
DWG No 58-6
REV
SCALE 3/8"=1'-0"
DATE 30JAN01

Or Simple Laminate Table

Transom Ring Frame			
Ply	Material	Fiber Orientation	Comments
1	12 C DB	45	4" flange
	300 g C uni's	0	5 cap plies (dk beam only)
2	12 C DB	0	3.75" flange
	300 g C uni's	0	5 cap plies (dk beam and frame)
3	12 C DB	45	3.5" flange
	300 g C uni's	0	5 cap plies (dk beam and frame)
4	12 C DB	0	3.25" flange
	300 g C uni's	0	5 cap plies (dk beam only)
5	12 C DB	45	3" flange
Notes:	1" fillet radius to hull		
	fabricated over 6 lb foam		

This Seminar's Focus

- Determining the appropriate amount of a given material
- Some information on selecting materials

Design Approaches

- Numerical methods (number crunching)
- Experimentation (prototypes)
- Empirical development (small changes each time)
- Plagiarism! (Not recommended if you are in college) Also called, “benchmarking”.

Numerical Structural Design Requires:

1. Geometry (what will the part look like, dimensions of length, width, maybe thickness)
2. Loads
3. Material properties, and
4. An analysis method (what theory to use)

The Most Fun Part is:

- Figuring out what it will look like!
  - In general, smaller parts require less structure, but also require more tooling costs and labor costs
  - Joints are expensive!
  - Aim for few parts

The Hardest Part is:

- What are the loads?
- Brainstorm on all the reasonable ways your customers can abuse your product!
- Did you think about high heels?

Did you think about waves?

Easiest Methods

- Combined methods (loads and analysis). Often called "Scantling Rules". Similar to a cookbook.
  - American Bureau of Shipping (ABS)
  - Lloyds, DnV, ISO, etc.
  - Gerr's Elements of Boat Strength
  - Herreshoff's, etc.

Advanced Methods

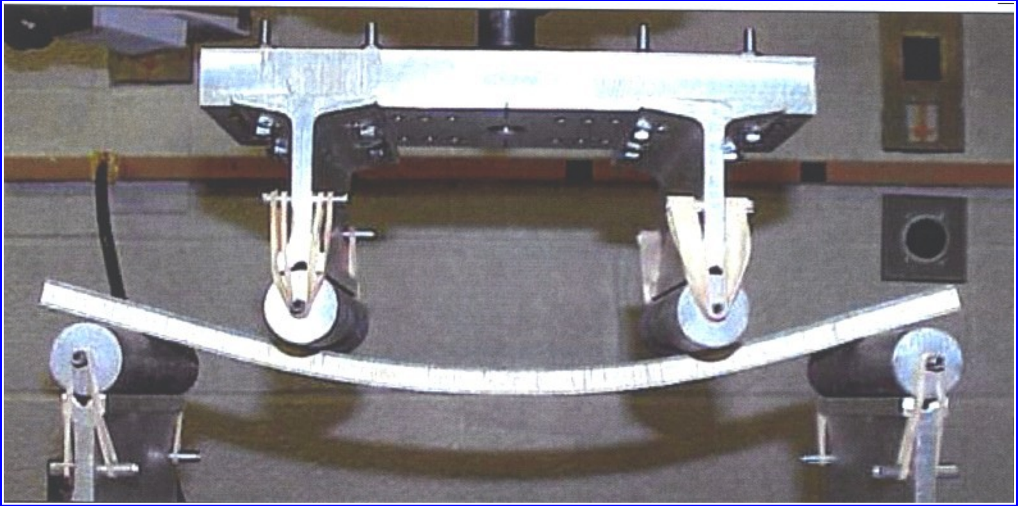
- Session 504 topics
- Loads calculated independently from structural theory
- CFD, LPT, CLT, FEA, TLA, etc.
- Potentially more accurate, so potentially lighter and less expensive –break even point?

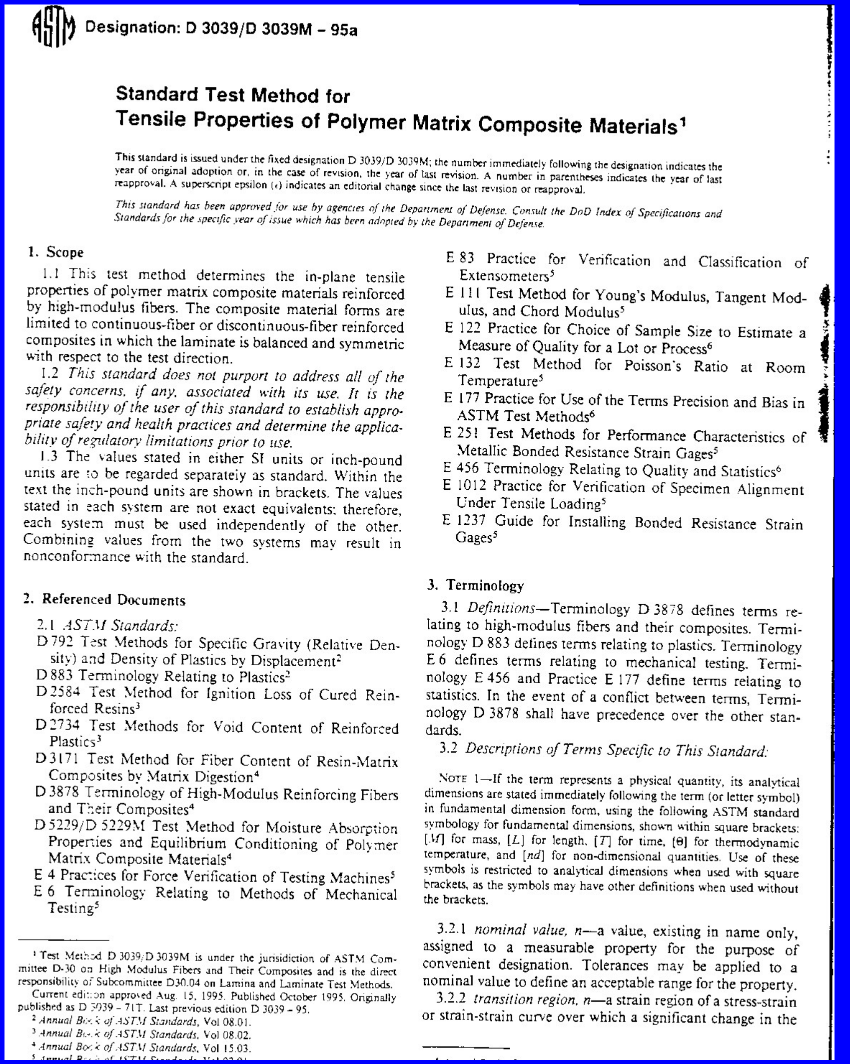
Material Properties

- To complete a design for strength
  - Tensile strength
  - Compressive strength
  - Shear strength
  - (Flexural strength)
  - Fatigue properties
- For stiffness driven designs
  - Modulus of Elasticity

How to get properties

- Tables
- Estimation
- Tests
  - Standard
  - Custom





Designation: D 3039/D 3039M – 95a

Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials[1]

This standard is issued under the fixed designation D 3039/D 3039M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 This test method determines the in-plane tensile properties of polymer matrix composite materials reinforced by high-modulus fibers. The composite material forms are limited to continuous-fiber or discontinuous-fiber reinforced composites in which the laminate is balanced and symmetric with respect to the test direction.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. Within the text the inch-pound units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

2. Referenced Documents

2.1 *ASTM Standards:*

D 792 Test Methods for Specific Gravity (Relative Density) and Density of Plastics by Displacement[2]
D 883 Terminology Relating to Plastics[2]
D 2584 Test Method for Ignition Loss of Cured Reinforced Resins[3]
D 2734 Test Methods for Void Content of Reinforced Plastics[3]
D 3171 Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion[4]
D 3878 Terminology of High-Modulus Reinforcing Fibers and Their Composites[4]
D 5229/D 5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials[4]
E 4 Practices for Force Verification of Testing Machines[5]
E 6 Terminology Relating to Methods of Mechanical Testing[5]
E 83 Practice for Verification and Classification of Extensometers[5]
E 111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus[5]
E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[6]
E 132 Test Method for Poisson's Ratio at Room Temperature[5]
E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[6]
E 251 Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages[5]
E 456 Terminology Relating to Quality and Statistics[6]
E 1012 Practice for Verification of Specimen Alignment Under Tensile Loading[5]
E 1237 Guide for Installing Bonded Resistance Strain Gages[5]

3. Terminology

3.1 *Definitions*—Terminology D 3878 defines terms relating to high-modulus fibers and their composites. Terminology D 883 defines terms relating to plastics. Terminology E 6 defines terms relating to mechanical testing. Terminology E 456 and Practice E 177 define terms relating to statistics. In the event of a conflict between terms, Terminology D 3878 shall have precedence over the other standards.

3.2 *Descriptions of Terms Specific to This Standard:*

NOTE 1—If the term represents a physical quantity, its analytical dimensions are stated immediately following the term (or letter symbol) in fundamental dimension form, using the following ASTM standard symbology for fundamental dimensions, shown within square brackets: [*M*] for mass, [*L*] for length, [*T*] for time, [θ] for thermodynamic temperature, and [*nd*] for non-dimensional quantities. Use of these symbols is restricted to analytical dimensions when used with square brackets, as the symbols may have other definitions when used without the brackets.

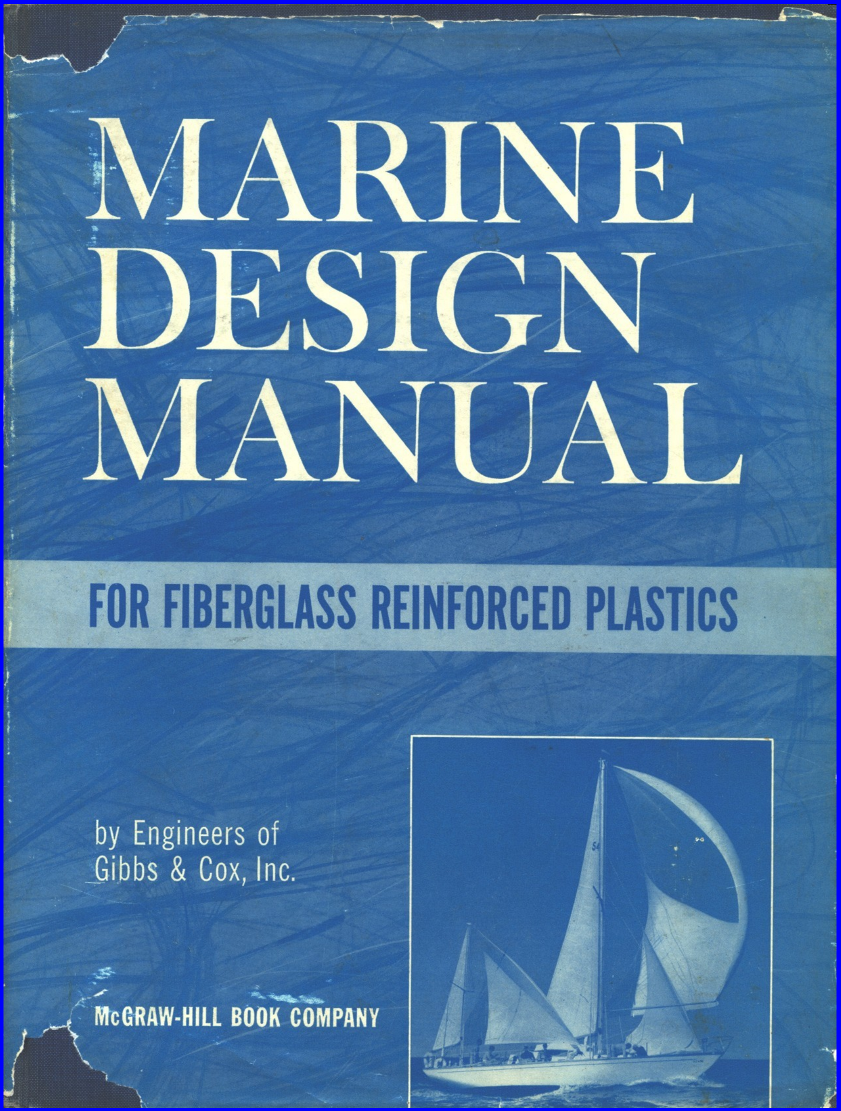
3.2.1 *nominal value, n*—a value, existing in name only, assigned to a measurable property for the purpose of convenient designation. Tolerances may be applied to a nominal value to define an acceptable range for the property.

3.2.2 *transition region, n*—a strain region of a stress-strain or strain-strain curve over which a significant change in the

[1] Test Method D 3039/D 3039M is under the jurisidiction of ASTM Committee D-30 on High Modulus Fibers and Their Composites and is the direct responsibility of Subcommittee D30.04 on Lamina and Laminate Test Methods.
Current edition approved Aug. 15, 1995. Published October 1995. Originally published as D 3039 – 71T. Last previous edition D 3039 – 95.
[2] *Annual Book of ASTM Standards*, Vol 08.01.
[3] *Annual Book of ASTM Standards*, Vol 08.02.
[4] *Annual Book of ASTM Standards*, Vol 15.03.

Tables

- Best Sources
  - Gibbs & Cox
    - (out of print)
  - Scott
  - Greene



Scott Tables

Example Fig 11

- **For a 45% resin content, all woven laminate typical of very good hand layup, tensile strength is 36000 psi**

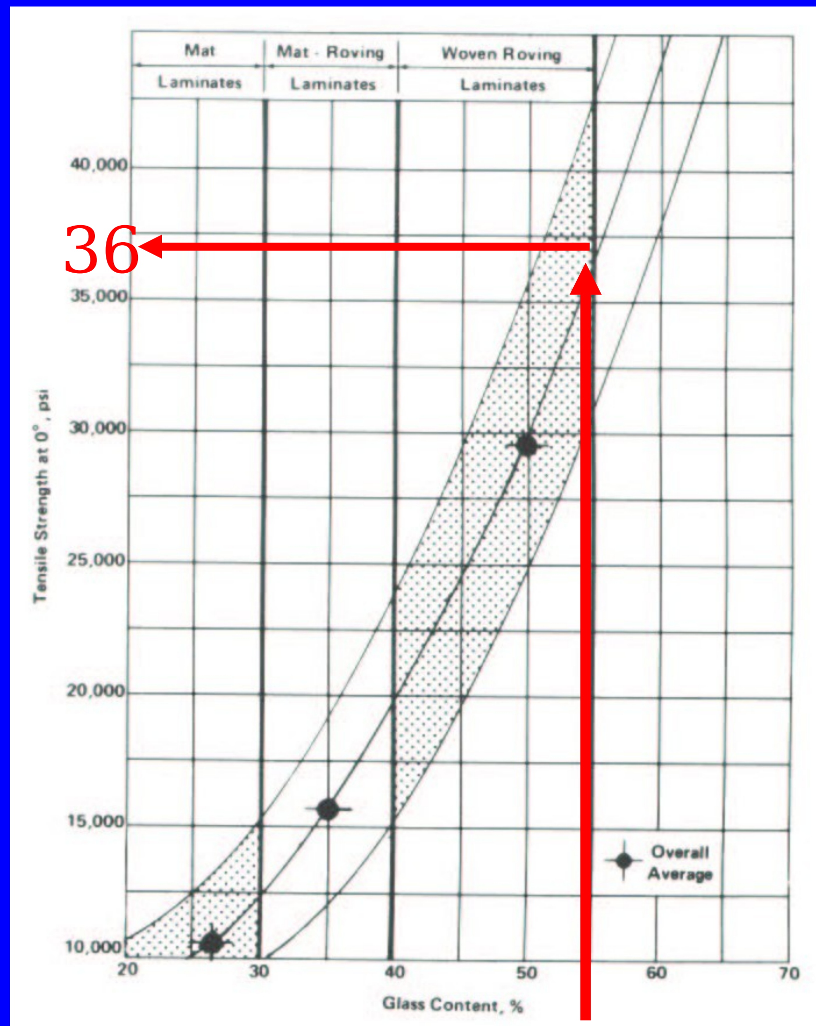
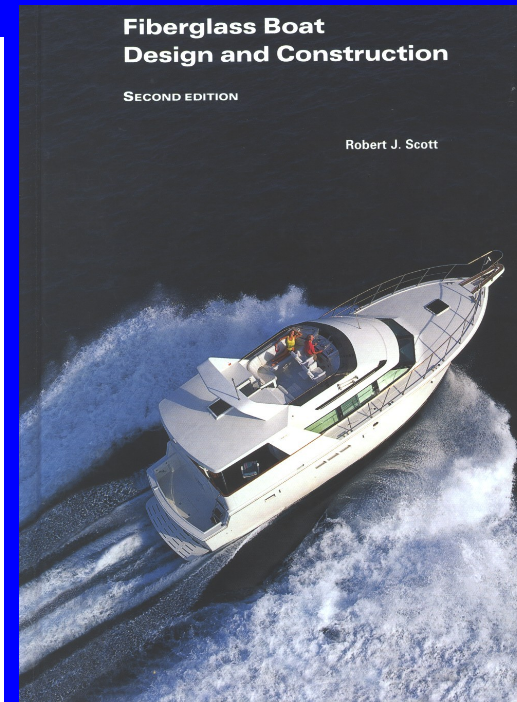


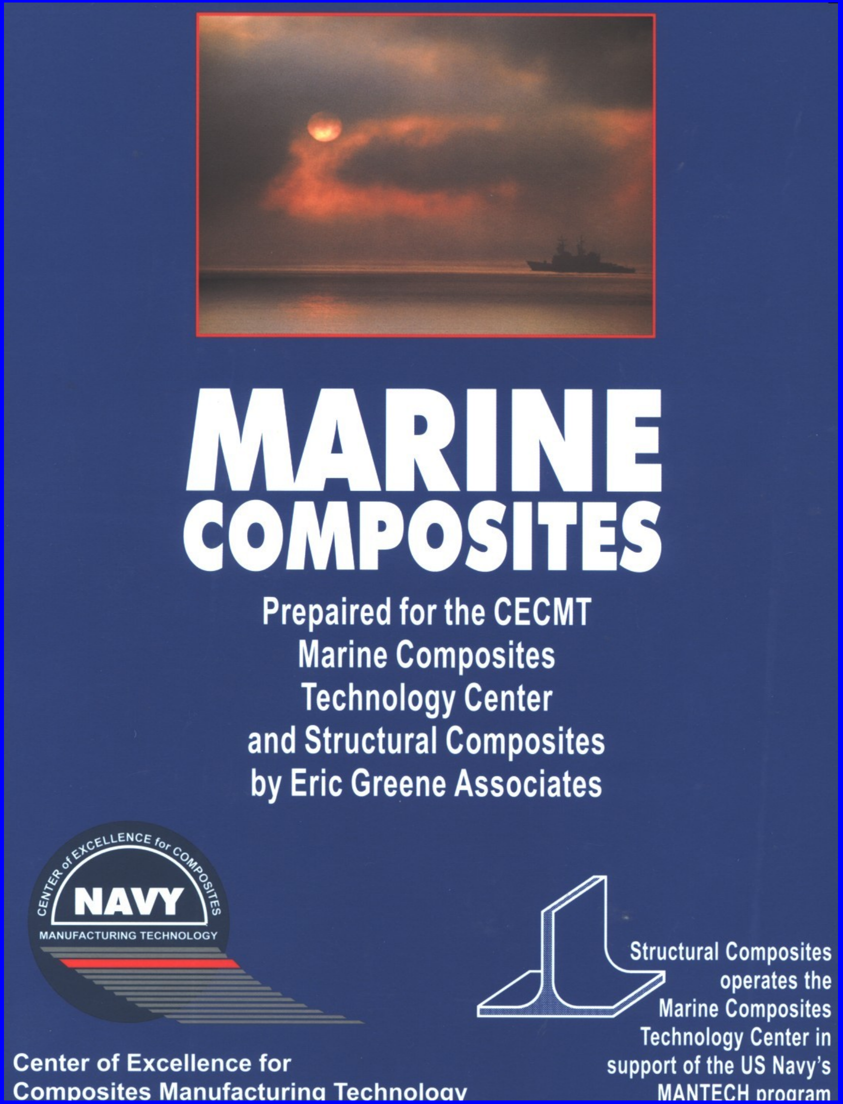
Figure 11
Tensile strength at 0 degrees (warp)



Only for typical mat, cloth and woven roving with polyester

Greene Tables

- **Appendix A**
- **Example**
  - **SCRIMP 7781/epoxy**
  - **34% resin content**
  - **Tensile strength is 56000 psi!**



www.marinecomposites.c
Free download!

Warnings!

- Tables are usually pretty good if you are using the same resin, cloth and workers as the person who tested them!
- Many have been burned!
  - 42000 psi compressive strength from carbon/epoxy?! That is half what the table told me!
- Maintain recommended factors of safety!

Property Estimation (from scratch)

- Micromechanics (Greene has a very good write-up)
- Example: Stiffness (E) of 55% glass-by-weight glass/polyester cloth laminate
- Step 1: Fiber volume

$$\mathit{fiber\,volume} = \frac{(1 - \mathit{void\,content})}{1 + \dfrac{\mathit{fiber\,density}}{\mathit{resin\,density}}\left(\dfrac{1}{\mathit{fiber\,weight}} - 1\right)}$$

$$\mathit{fiber\,volume} = \frac{(1 - 0.03)}{1 + \dfrac{162}{77}\left(\dfrac{1}{0.55} - 1\right)} = 35.6\%$$

Estimation (con't)

- **Step 2 Estimate perfect laminate**
  - R

$$E_{lam} = fibervolume(E_{glass}) + (1 - fibervolume)(E_{resin})$$

$$E_{lam} = 0.356(10.5 msi) + 0.644(0.59 msi)$$

$$E_{lam} = 4.1 msi$$

- **Step 3 Realize cloth is not all in tion!**

$$E_{cloth} \cong (50\%)(E_{lam})$$

$$E_{cloth} \cong 0.5(4.1 msi)$$

$$E_{cloth} \cong 2.0 msi$$

Which is about the same as S

(We were lucky!)

Estimation (con’t)

- Step 4
  - Count your blessings if you got a reasonable number and maintain normal factors of safety (2-5)!
- Step 5
  - Try to convince management to pay for a few tests!

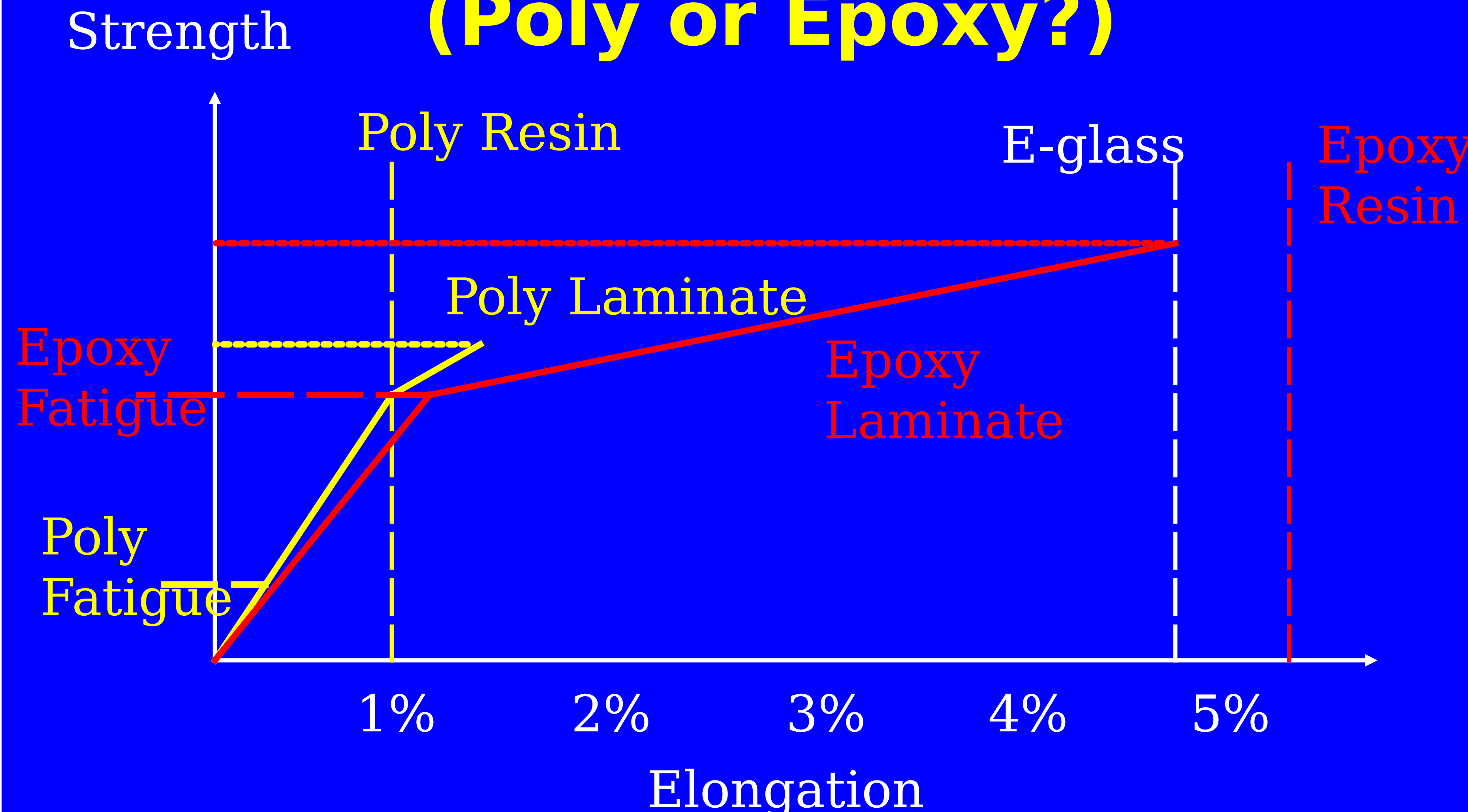
Thoughts on Materials

- Boats they are used much see a lot of fatigue (waves, dockings, etc.)
- Fatigue strengths for a vessel in service for 10 years may be as little as 20% of original values!
- Brittle resins drive fatigue problems!

Simple Composite Fatigue Theory (Dharan)

- Fatigue endurance limit is 25% of the failure strain of the resin or fiber, whichever is less
- Failure Strain (elongation) is the percent the material has stretched when it fractures
  - Poly ~ 1%, VE ~ 3-15%, Epoxy ~3-15%
  - Glass ~ 4-6%, Carbon ~ 0.4-2%

Design for Fatigue
(Poly or Epoxy?)



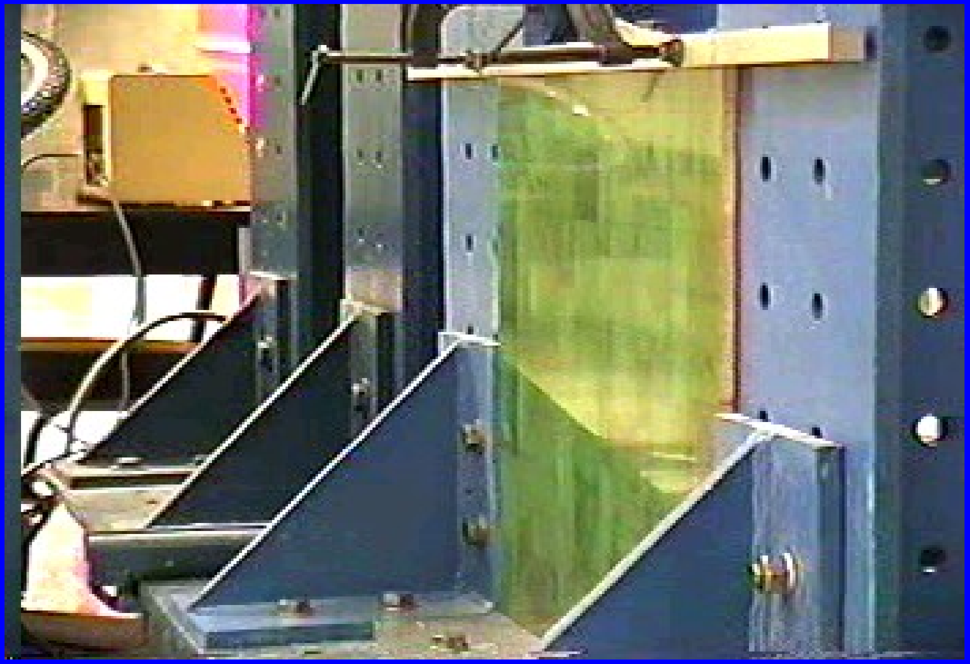
Note: The epoxy laminate is only slightly stronger, but has a much higher fatigue limit! This means the FOS could be lower.

Fatigue Rule of Thumb

- If you want something to last for a long time in operation, choose a resin that has an elongation at failure slightly higher than the fiber you use.

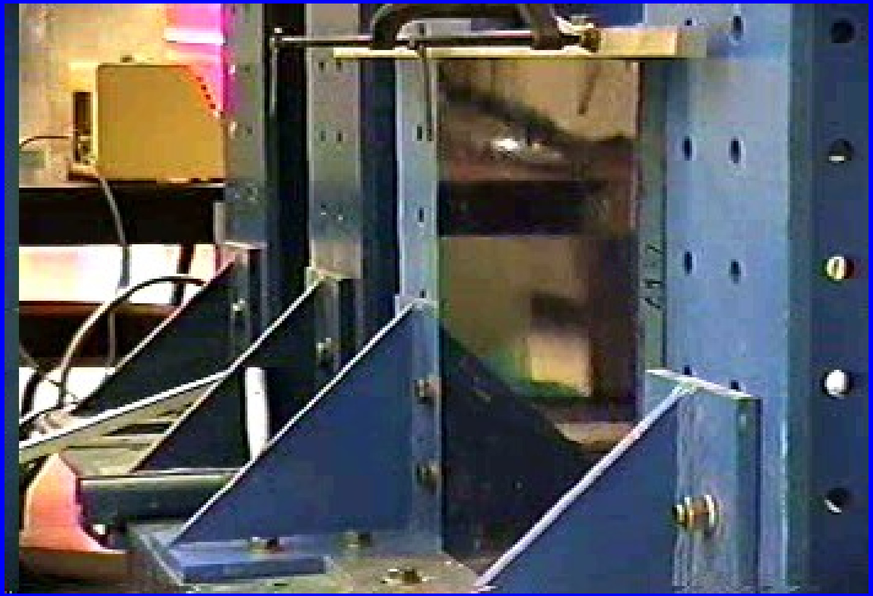
Material/Component Testing

- Test some materials to get peace of mind
- Prototyping
  - “potato chip”
- Self Experimentation
  - Navy 44
- Test labs (ASTM style tests)

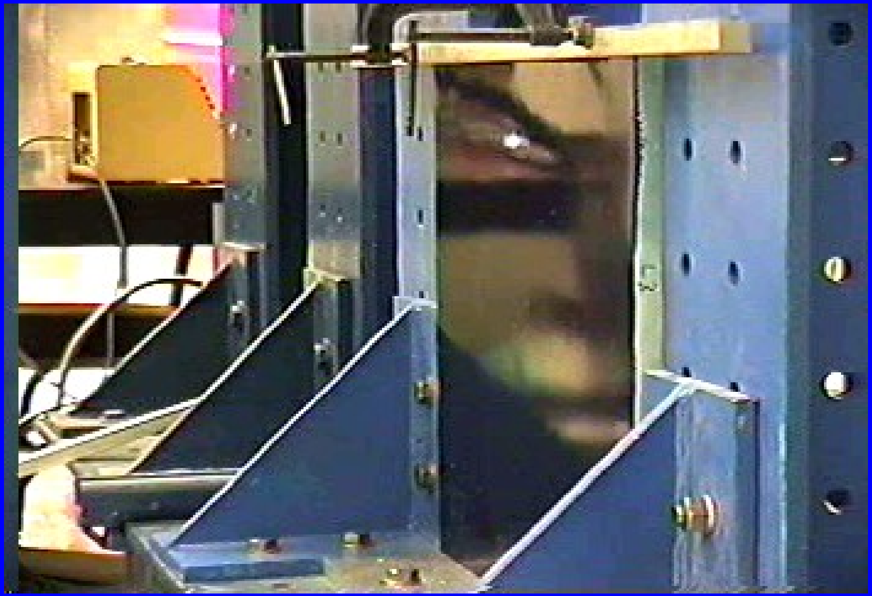


Cheapest laminate
Try #1!

More Tests



Most expensive laminate
Try #7!
300% more expensive than the first.



Final laminate
Try #23!
Only 40% more expensive than the first, third cheapest

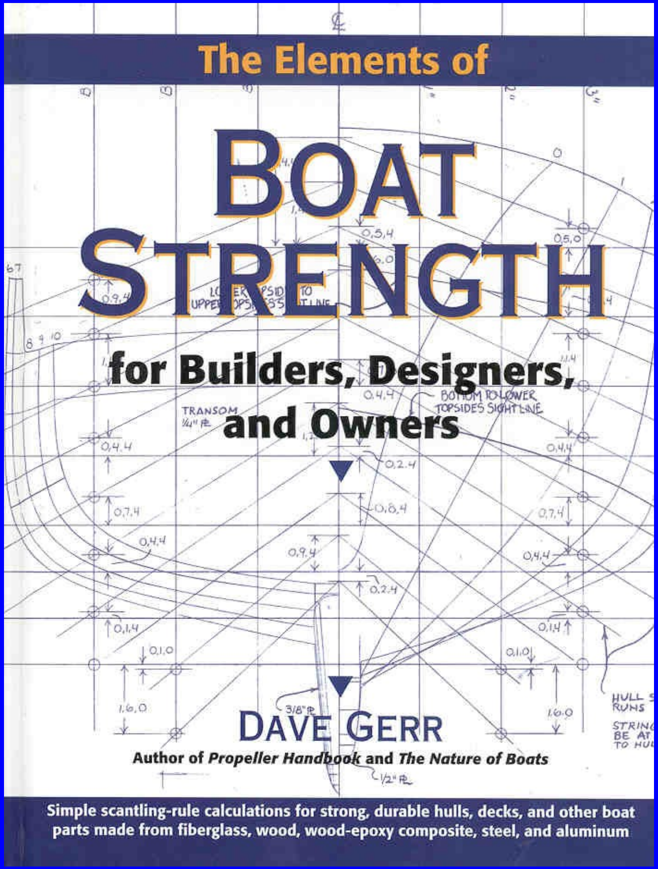
Cost of testing was $8K, cost savings for 24 boats was ~

Testing Rule of Thumb

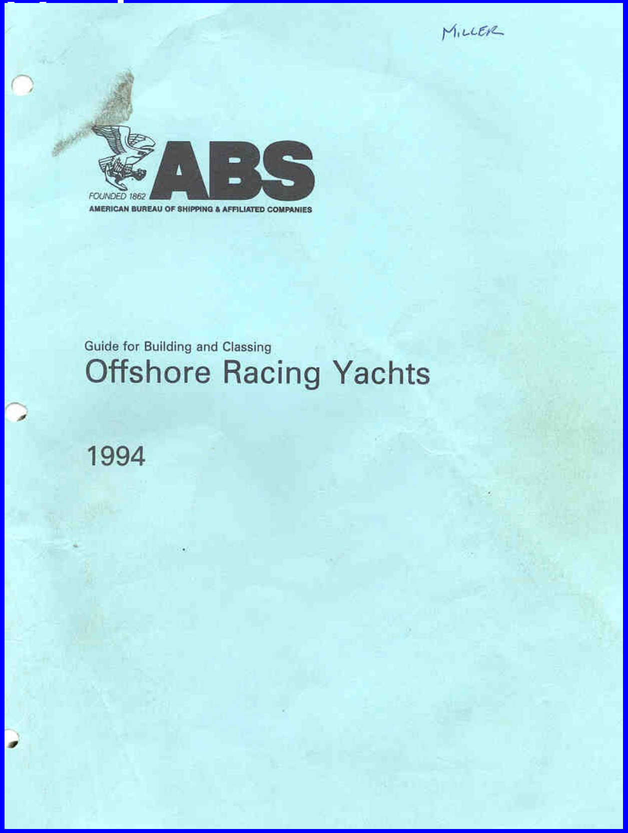
- Current theory can not predict all responses!
- Choose a test most appropriate to your application.
  - Boiling test inappropriateness
- Greene has good summary of common tests

Two Scantlings Methods

The Elements of Boat Strength by Dave Gerr



American Bureau of Shipping Guide for Building and Classing Offshore Racing



Design Example! Scantlings Method

- What should the hull laminate (solid skin – roving/mat/poly) be for a 30 foot sailboat?
- Beam is 10’, Draft 4’, Canoe body depth is 6.5’ and weight is 7500 lb.
- Easiest methods are Gerr and Scott.
- Stopwatches On!

Gerr Method

- Formula 1-1
  - Sn= 30’ x 10’ x 6’8” /1000
  - Sn= 2
- Formula 4-1(and figure)
  - Lower topside thickness is 0.31”
- Formula 4-2
  - Bottom is 1.15 x Lower topside
  - Bottom is 0.36” thick
- Table 4-9
  - 24-15 Combi is 0.089” so 4 plies!

Gerr (con’t)

- Weight is about 0.75 lb/sq ft per ply of 24-15 combi (see Scott Figure 32), so about 3 lb /sq ft for this laminate.
- Formula 5-5 indicates 6 frames
- Total time was about 5 minutes.
- A good way to start!

ABS Method

- **Offshore Yacht Guide**
- **Section 4.5.4 calls for Combi as standard laminate (Table 4.3)**
- **Section 7.3.1 thickness is lower of**

Strength egn

$$t = sc\sqrt{\frac{pk}{\sigma_a}}$$

$$t = 0.75sc\sqrt[3]{\frac{pk_1}{0.02E}}$$

Stiffness

S=frame spacing
C=curvature correction
P=load
K=panel aspect ratio
σ=strength
E=modulus

ABS (con't)

- S=51.4 in (for comparison)
- C=0.7
- P=0.44Fh, F from Table 7.4 = 0.25
- h from Table 7.1 = 15 ft x 1.2 for slamming = 18 ft
- K from Table 7.3 = 0.47

∀ σ from Table 7.2 = 0.5 x 25000

ABS (con't)

- So, from the first equation,

$$t = (514)(0.7)\sqrt{\frac{(0.44)(0.25)(18)(0.47)}{0.5(250000)}}$$

$$t = 0.31$$

- And for the second
  - K1=0.024
  - E = 1.1msi

$$t = (0.75)(514)(0.7)\sqrt[3]{\frac{(0.44)(0.25)(18)(0.024)}{0.02(1.1E6)}}$$

$$t = 0.35$$

Comparison

- ABS gave 0.35” and Gerr 0.36”!
- ABS took 30 minutes, Gerr 5
- ABS more flexible in material properties (note that if the “good” laminate in Scott was used, the thickness would be 0.3”)
- ABS open to design geometry variation and has a longer track record.
- Scott method based on ABS, but more general
- Greene uses DnV and general equations
- Note that these were relatively simple examples!

For Other Components

- Use the equations in Scott, Greene and “Roark’s Formulas for Stress and Strain” if you have some engineering background
- Seriously consider a prototype or

Recommendations for Basic Marine Composites Design

- Start with Scott for an overview
- If you are starting from scratch, start with Gerr for the big pieces, use Scott or Greene for preliminary material properties
- Decide if prototype testing makes sense
- Get test values of your laminates and use ABS for a second opinion
- Don’t stray too far from the assumptions made by the authors!

More Advice!

- If you have some engineering background, use the more advanced formulas in Greene, Scott and Roark’s.
- Attend Session 504 for more advanced, and potentially rewarding, techniques!
- Keep a mental list of “the 10 dumbest places to save weight on a boat”!

Contact Information

Paul H. Miller

Phmiller@usna.edu

410-293-6441

Google “Paul H. Miller” for my webpages